Biomechanical modeling to prevent soft tissues pressure ulcers

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INTRODUCTION

Pressure ulcers (PU) affect almost half of the patients in reanimation or geriatric units. They are localized injuries that affect the skin and underlying soft tissues, usually below a bony prominence. The main suspected causes are the excessive pressure intensity (internal tissue strains above 50 % for about 10 minutes) or prolonged compression (internal strains above 20 % for about two hours) [1]. Specific forms of PU, termed Deep Tissue Injuries (DTI), are defined as pressure-related injury to subcutaneous tissues such as skeletal muscles [2]. DTI start in deep tissues underneath an intact skin and progress outward rapidly, causing substantial subcutaneous damages before being visible. Prevention through daily examination lacks efficiency because of the nature of DTI: when visual symptoms appear, it is often too late to prevent dramatic injuries. Measuring surface pressures is believed to be effective in alerting patients at risk against focal pressures that may cause soft tissues injury [3], but these measurements cannot predict dangerous internal tissue loading [4]. For example, similar pressures may be observed under the buttocks of a heavy paraplegic person with sharp ischial tuberosity (IT) and a thin person with blunt ITs; however, their susceptibility to DTI depends on the IT curvature as well as the thickness of the soft tissues which lead to different internal strains creating the injuries [5]. It is consequently crucial to monitor these internal strains. The only way to estimate these strains from the skin surface pressures is to build a patient-specific biomechanical model of the soft tissues and the bony prominences. PU are frequent in reanimation and geriatric patients, especially at two locations: the buttocks (below the ischial tuberosities and the sacrum) and the foot (below the heel). In this study, we therefore introduce two generic models of the buttocks and of the foot that can be used as a foundation to create patient-specific biomechanical models with the objective of personalized PU prevention.

METHODS

Our foot and buttocks models have been developed using the 3D biomechanical simulation platform, Artisynth [6]. The models are composed of bones and soft tissues, including skin, muscles and fat. On top of these, the foot model includes ligaments and joints. The surfaces of these structures (skin, muscles and bones) are inspired by the surfaces from the zygote database (www.zygote.com) for the foot and segmented from a young healthy subject for the buttocks. Using an automatic Finite Element (FE) mesh generator [7], the surfaces were filled with elements based on a hexahedral grid,

completed with wedges and tetrahedrons to maximize the accuracy and to ensure continuity between structures. The bones are modeled as rigid solids. Figures 1 and 2 plot the corresponding FE meshes.

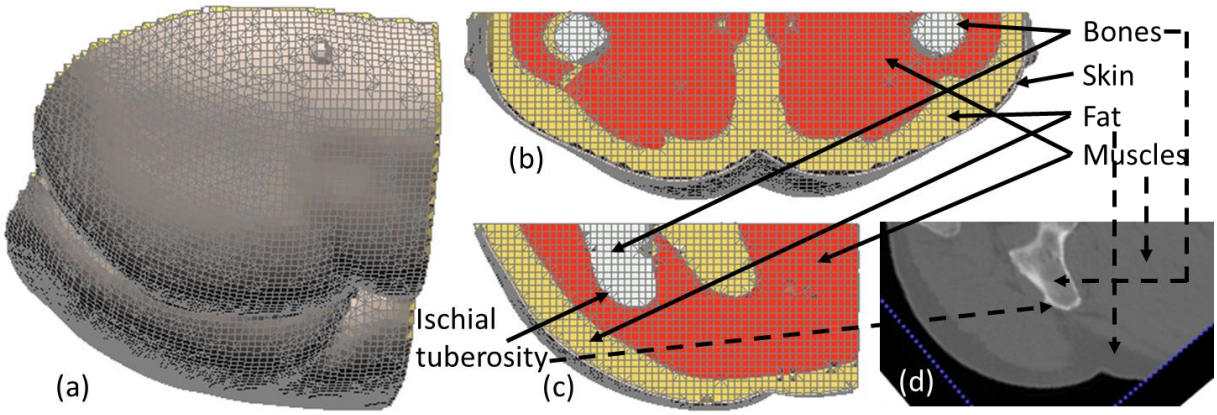

Figure 1. (a) Finite element model of the buttocks; (b) frontal and (c) and sagittal cross sections showing the three layers of materials defining the buttocks model: skin (in grey), fat (in yellow) and muscles (in red); the bones are represented in white and are simulated as fixed nodes; (d) CT scan slice showing the ischial tuberosity surrounded by muscles and fat tissues.

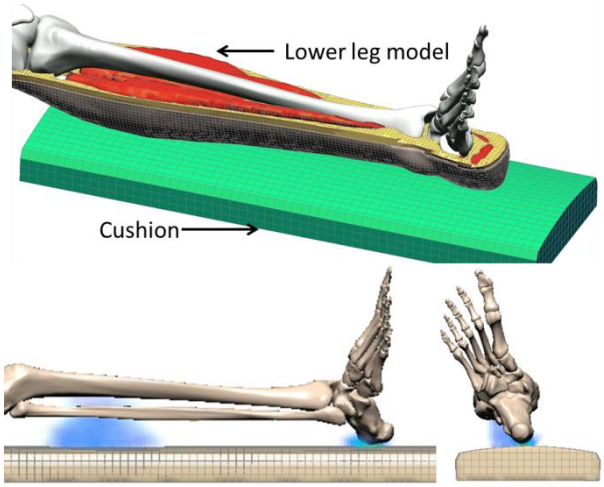

Figure 2. Top: the four types of materials defining the lower leg FE model: skin (only one layer of elements around the leg), muscles (in red), fat (in yellow), and Achilles tendon. Bottom: clusters of the nodes with VM strains above 20 %. The maximum VM strain (57 %, in red) is located under the heel, at the interface between fat and calcaneus.

The buttocks FE mesh (Fig. 1) models the soft tissues representing the skin, muscles and fat using three different Neo Hookean materials, as those tissues undergo large deformations following an hyper elastic behavior, with Young moduli set to 200 kPa for the skin, 100 kPa for the muscles, and 30 kPa for the fat. All materials have a Poisson ratio of 0.49.

For the foot FE mesh (Fig. 2), the soft tissues are modeled as four different Neo Hookean materials with Young moduli set to 200 kPa for the skin, 100 kPa for the muscles, 1 GPa for the tendon, and 30 kPa for the fat. All materials have a Poisson ratio of 0.495, except for the fat with a value of 0.49 [5]. The 26 foot bones are modeled as rigid body surfaces coupled to the nearby FE nodes. The 33 foot joints are simulated by pivots connecting each bone with its neighbors.

RESULTS

Biomechanical models can be used to simulate the behavior of the buttocks or the foot under different constraints. They can compute the internal strains and stresses in the subcutaneous tissues under various external patterns of pressures applied at the skin surface, and therefore predict the risks for DTI development. For example, the bottom panel of figure 2 plots the levels of internal strains due to the contact of the lower leg on a soft cushion. This kind of simulations could allow specifically assessing the influence of the calcaneus bone geometry on the risk of PU creation, or the influence of the cushion stiffness. In this case, a cushion with a soft stiffness seems to limit the risk in terms of short term PU creation, while cushions mildly inflated under one of the sections of the leg leads to a risk of PU creation in a time period around two hours (since the 20 % VM strain threshold is reached in all cases [1]). The same kind of behavior can be observed for the buttocks. Thanks to these biomechanical models, it is consequently possible to define a time threshold, a pressure threshold, or a cushion stiffness threshold, that should prevent PU.

DISCUSSION

Our biomechanical models allow simulating the foot and buttocks with a realistic behavior in terms of surface and internal pressures. These constraint analyses resulting from a prescribed load could consequently determine if and when pressure ulcers may appear. Our future works will aim at automatically creating patient-specific models from these generic models and to couple them interactively with data provided by the "TexiSense Smart Sensor" that could provide a daily personalized PU prevention [8].

ACKNOWLEDGEMENTS

This work was carried out with the financial support of IDS Company, Carnot LSI Institute, the Labex CAMI (ANR-11-LABX-0004), the Institut Universitaire de France and the French national research project ANR/TecSan 2010 IDSocks.

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